

# CLUSTERS OF GALAXIES: MULTIFREQUENCY OBSERVATIONS VERSUS THEORIES

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**ABSTRACT.** Clusters of galaxies are large gravitationally bound systems which consist of several observable components: hundreds of galaxies, hot gas between the galaxies and sometimes relativistic particles. These components are emitting in different wavelengths from radio to X-rays. We show that the combination of observations at different frequencies and also theoretical models is giving now a comprehensive picture of these massive objects. Topics presented here include cluster masses, baryon fractions, the dynamical state of clusters, the physical processes in clusters and cosmological parameters derived from cluster observations.

## 1. Introduction

Clusters of galaxies were first detected as large concentrations of galaxies. With the advent of X-ray astronomy also X-ray emission from galaxy clusters was found. This emission could be explained as thermal bremsstrahlung from hot gas filling the whole potential well of the cluster (e.g. Sarazin 1986). Moreover, in many clusters radio emission was found. This radio emission is synchrotron emission from relativistic particles. Table 1 summarises the main cluster components together with their mass fractions. While galaxies contribute only 3 – 5% to the cluster mass, the contribution of the gas is considerably more (10 – 30%; see e.g. Arnaud & Evrard 1999; Ettori & Fabian 1999). But, as these two contributions are by far not 100%, it is concluded that most of the mass is in form of dark matter, i.e. not directly observable. Therefore mass determinations, which are indirect measurements of the dark matter, are so particularly interesting in clusters.

The list of components summarises only the main cluster components and main frequencies, at which clusters are observed. Of course this list is not complete, and clusters are also observable at other frequencies, e.g. non-thermal, hard X-ray emission was detected in some clusters (see Fusco-Femiano et al. 1999). In the following several fields of cluster research are presented. Also this compilation cannot be complete with only limited space available. Only a few topics could be selected and handled very briefly. Preference was given to currently very active fields which combine observations in two or more wavelengths.

**Tab. 1 - Main cluster components**

	mass fraction	observable in
galaxies	3 – 5%	optical
intra-cluster gas	10 – 30%	X-rays (thermal bremsstrahlung)
relativistic particles	-	radio (synchrotron emission)
dark matter	rest	-

## 2. Optical observations

Historically, optical observations were the first cluster observations. Already from the first cluster catalogues (e.g. Abell 1958) a rough estimate of the richness and the morphology of cluster could be obtained. With the additional information of the velocity of the galaxies three aspects can be addressed: (1) the redshift measurement yields the three-dimensional distribution of clusters, which is very important for cosmological studies, i.e. the determination of distribution functions. (2) The distribution of velocities within a cluster gives information about the internal dynamics, i.e. the collision of two subclusters can show up as a broadened velocity distribution (e.g. Binggeli et al. 1993). (3) With the assumption of virial equilibrium the velocity dispersion (= the standard deviation of the distribution) yields a measure for the total cluster mass (see e.g. Carlberg et al. 1996; Girardi et al. 1998). In this way Zwicky found already in 1933 that not all the cluster mass can be contained in the galaxies. Detailed spectroscopic and morphological studies of distant cluster galaxies provides interesting information on cluster formation and evolution (e.g. Stanford et al. 1998, van Dokkum et al. 1998). The morphological types of galaxies are not distributed in uniformly, but the higher the galaxy density the larger is the fraction of ellipticals (Dressler 1980). This holds not only for a comparison of the field galaxies with cluster galaxies, but also for cluster galaxies at different distances to the cluster centre. This effect can be well seen e.g. in the Virgo cluster (Binggeli et al. 1987; Schindler et al. 1999; see Fig. 1). The explanation for this density-morphology relation is interaction between galaxies and interaction of galaxies with the intra-cluster gas. A beautiful example of the latter can be seen again in the Virgo cluster in HI: two galaxies are stripped off their cool gas when approaching the cluster centre (Cayatte et al. 1990).

A currently very active field is gravitational lensing. Since the first arcs in clusters were discovered more than 10 years ago (Lynds & Petrosian 1986; Soucail 1987) gravitational lensing was used as a way to determine cluster masses. Two methods to determine the mass can be distinguished: strong lensing and weak lensing. Strong lensing uses the giant arcs which are distorted images of background galaxies, see e.g. the beautiful HST images of Cl0024+1654 (Colley et al. 1996) and A2218 (Kneib et al. 1996). With this method only the mass contained in a volume within the arc radius can be measured, i.e. it is restricted to the central part of the cluster. Weak lensing on the other hand uses the systematic elongation of all background galaxies. With a few mathematical operations – a method pioneered by Kaiser & Squires (1993) – this can be directly transformed into a mass distribution without treating different subclusters or single galaxies separately.

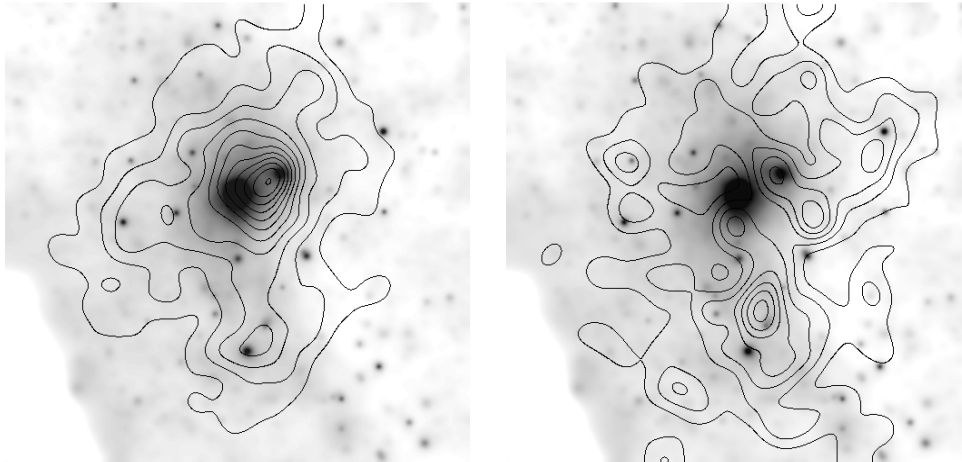


Fig. 1. X-ray emission of the intra-cluster gas (greyscale image) from the Virgo cluster in the ROSAT All-Sky Survey. Superposed on the X-ray image are contours of constant galaxy number density of different morphological types. The dwarf elliptical galaxies (left) show a very centrally concentrated distribution – similar to the distribution of the gas. The spirals and irregulars (right) are much more dispersed and the density maxima do not coincide with the X-ray maxima.

The difficulties for this method are the distinction of background galaxies and the normalisation of the mass, because the mass distribution cannot be measured out to border of the cluster due to the limited CCD sizes. An example for a weak lensing analysis for the cluster A2218 and a comparison of the different mass determination methods can be seen in Squires et al. (1996). For a recent reviews on lensing in clusters see Hattori et al. (1999) and for lensing in general see Wambsganss (1998).

### 3. X-ray observations

The gas between the galaxies is so hot, that it is emitting thermal bremsstrahlung in X-rays. This hot gas is filling the whole cluster potential and is therefore a good tracer for deep potential wells. As the thermal bremsstrahlung is proportional to the square of the gas density, X-ray selected clusters are much less affected by projection effects than optically selected clusters. Furthermore, the morphology of a cluster can be seen much better in X-rays, even for distant clusters. Two examples of clusters with very different morphologies (see Fig. 2) at similar redshifts ( $z \approx 0.4$ ) are Cl0939+4713 – a cluster with two subclumps each of them showing even some internal structure (Schindler et al. 1998) – and RXJ1347-1145 – the most X-ray luminous cluster found so far with a very centrally concentrated X-ray emission (Schindler et al. 1997). The morphologies are important for cosmology. In a low  $\Omega$  universe the merging processes should stop earlier so that more clusters with virialised X-ray emission are expected. Therefore the fraction of virialised clusters at a certain redshift can be used to constrain the mean density of

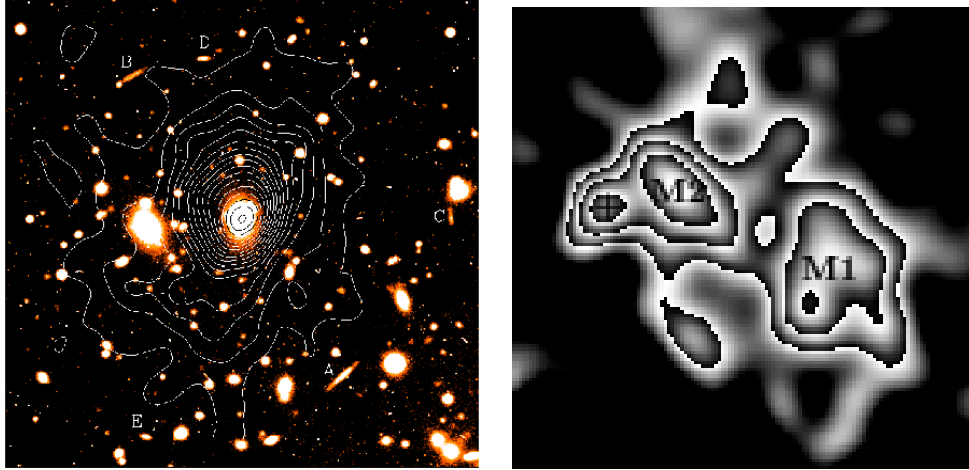


Fig. 2. Two clusters at redshift  $z \approx 0.4$  with very different X-ray morphology. RXJ1347-1145 (left) – the most X-ray luminous cluster – shows a very compact gas distribution in X-rays (contours). The contours are superposed on an optical image. Several arcs around the centre (marked by letters) show that the cluster is acting as a gravitational lens. The cluster Cl0939+4713 (right) shows a very different gas distribution. Two subclusters marked with M1 and M2 are visible, which have even some internal structure. The maximum marked with a “plus” sign is not cluster emission, but is caused by a background quasar at  $z = 2$ . The size of the two images is very different: the image of RXJ1347-1145 is  $1.5 \times 1.5$  arcminutes<sup>2</sup>, while image of Cl0939+4713 is  $3.7 \times 3.7$  arcminutes<sup>2</sup>.

the universe  $\Omega$  (for theory see Richstone et al. 1992; for an application to observations see Mohr et al. 1995).

While recent morphological studies were carried out mainly with ROSAT observations, the Japanese satellite ASCA was much used because of its spectral capabilities. An important parameter determined by X-ray spectra is the gas temperature. The temperature is typically between 1 and 10 keV being in good agreement with the depth of the potential well. Temperature maps, which are still very coarse due to the limited spatial resolution of ASCA, show that many clusters are not isothermal (Markevitch 1998). The temperature distribution is another way to determine the dynamical state of a cluster. As it was shown by hydrodynamic simulations (Schindler & Müller 1993) the temperature structure shows very clearly the different stages of a merger, e.g. the hot, compressed gas between two subclusters shortly before they collide or the shock waves emerging after the collision as steep temperature gradients.

As not all the ions are completely ionised at these temperatures line emission can be observed. In most of the clusters Fe lines are visible, but sometimes also Si and other elements are detectable. The metallicities (calculated from the Fe lines) are typically in the range between 0.2 and 0.5 in solar units (e.g. Mushotzky & Loewenstein 1997; Tsuru et al. 1997; Fukazawa et al. 1998). Obviously, the gas cannot be purely of primordial origin but must have been enriched by nucleosynthesis processes in cluster galaxies. No

(strong) evolution of the metallicities with time has been found out to a redshift of 1 (Schindler 1999). This result is in agreement with optical observations of cluster galaxy evolution (e.g. Stanford et al. 1998) and theoretical models (Martinelli et al. 1999), which both find no metal enrichment of the intra-cluster medium for redshifts smaller than 1, i.e. the enrichment must take place relatively early. A famous example for a high-redshift and high-metallicity cluster is the cluster AXJ2019+112 at a redshift of  $z = 1$ , which has a puzzling iron abundance of more than the solar value (Hattori et al. 1997).

X-ray observations provide another method to measure the cluster mass. With the assumption of hydrostatic equilibrium the mass can be estimated simply from the temperature profile and the gas density profile (for applications of this method on a large sample of clusters see e.g. Arnaud & Evrard 1999; Ettori & Fabian 1999). Numerical simulations showed that hydrostatic equilibrium is a good assumption to get reasonable mass estimates in roughly relaxed clusters (Evrard et al. 1996; Schindler 1996). Masses for typical clusters are of the order of  $10^{15} M_{\odot}$  when measured out to the virial radius. A comparison of the masses determined by the different methods shows that the virial mass and the X-ray mass are in general in agreement, but the lensing mass (in particular the mass from strong lensing) is sometimes up to a factor of three higher (see e.g. the comparison in Squires et al. 1996 or Schindler et al. 1997). In these comparisons it is important to take into account that the mass is measured in different volumes: in X-rays the mass is measured in a spherical volume, while the gravitational lensing effect is sensitive to all the mass along the line-of-sight, i.e. it measures the mass in a cylindrical volume around the cluster. Therefore, the measurements can give different results, although they are all correct. As the measurements for all the methods mentioned here are getting better and the problems of the individual methods (like e.g. projection effects) are better understood, it is probable that all the methods are going to converge in the end.

From the X-ray observations also the mass of the intra-cluster gas can be determined. Together with the mass in the galaxies this yields an average baryon fraction of about 20%. For an  $\Omega = 1$  universe this value is at least 3 times larger than allowed by primordial nucleosynthesis – a famous discrepancy termed “baryon catastrophe” (White et al. 1993). The easiest way out of the problem seems now a cosmological model with a low  $\Omega$ .

A comparison of the gas distribution and the dark matter distribution shows that the gas distribution is generally more extended (e.g. David et al. 1995). Obviously, cluster evolution is not completely a self-similar process, but physical processes taking place in the gas must be taken into account, like e.g. energy input by supernovae, galactic winds or ram-pressure stripping (see e.g. Metzler & Evrard 1997; Cavaliere et al. 1998a). As the gas distribution is relatively more extended in less massive clusters (see Schindler 1999) these heating processes must be more efficient in less massive clusters.

Clusters as the largest bound objects in the universe are very good tracers for large-scale structure. They can be used for various cosmological tests. Distribution functions like the luminosity function (e.g. De Grandi et al. 1999) or the correlation function (e.g. Guzzo et al. 1999) preferably of an X-ray selected cluster sample (i.e. a mass selected sample) can be used to constrain cosmological parameters. Also correlations between X-

ray quantities (e.g. between the X-ray luminosity, the temperature and the cluster mass) can be used to test different cosmological models because their relations as well as the evolution of these relations depend on cosmological parameters (Oukbir & Blanchard 1992; Bower 1997; Cavaliere et al. 1998b, Eke et al. 1998; Schindler 1999).

#### 4. Radio observations

Radio emission has been found in many galaxies clusters. Two different kinds of radio emission can be distinguished: diffuse emission and emission associated with galaxies. The latter one (see Owen & Ledlow 1997 for many examples) can be used to determine the relative motion of the intra-cluster gas and head-tail galaxies by their radio morphology (O'Donoghue et al. 1993; Sijbring & de Bruyn 1998). Furthermore, the pressure of the intra-cluster gas can be estimated from the radio lobe expansion into the gas (e.g. Eilek et al. 1984; Feretti et al. 1990). Observations of the rotation measure of sources in or behind a cluster provide the possibility to determine the cluster magnetic field. Typically values between  $0.1 \mu\text{G}$  up to few  $\mu\text{G}$  are found (e.g. Feretti et al. 1995).

In several clusters diffuse radio emission could be detected (e.g. Giovannini et al. 1999). If the diffuse emission is located in the central parts and has a roughly spherical shape, it is called radio halo, see e.g. the Coma cluster (Giovannini et al. 1993). In other clusters the radio emission is situated in the outer parts and has usually elongated shapes. These sources are called relics, see e.g. A3667 (Röttgering et al. 1997). Although it was previously assumed that the central and non-central sources are different kinds of sources, it is now probable that they have the same origin. A possible explanation for the emission could be merging of subclusters. In such mergers turbulence and shocks are produced which can provide the necessary energy to reaccelerate particles and to amplify the magnetic field. The discovered correlations between the halo size, the radio power, the X-ray luminosity and the gas temperature of the host cluster support this theory: The collision of more massive clusters (= higher X-ray luminosity and higher gas temperature) would provide more energy for the radio halo.

Finally, a very exciting field, which uses a combination of radio and X-ray observations, is the distance determination by the Sunyaev-Zel'dovich effect (Sunyaev & Zel'dovich 1972). When photons of the cosmic microwave background pass through the hot gas of a cluster, they are scattered to slightly higher energies, i.e. inverse Compton scattering. That means the blackbody spectrum of the CMB appears slightly shifted when observed in direction of a cluster. This results in an increment or a decrement depending on what side of the blackbody spectrum the observations are done. This in- or decrement is proportional to the intra-cluster gas density, while the X-ray emission is proportional to the square of the density. These two different dependences allow to estimate the physical size of the cluster, while the angular size of the cluster can be measured easily. The combination of physical and angular size provides a direct measurement of the distance of the cluster. The problem of this method is that the physical size is measured along the line-of-sight, while the angular size is measured perpendicular to the line-of-sight, i.e. if the cluster is elongated the derived distance is wrong. To avoid this problem currently whole samples of clusters are measured (e.g. Carlstrom et al. 1999), because for many clusters this effect is expected to average out. Further-

more, the Sunyaev-Zel'dovich effect can also be used to study the distribution of the intra-cluster gas. For a recent review on the Sunyaev-Zel'dovich effect see Birkinshaw (1999).

## 5. Conclusions

The study of clusters of galaxies became a very active field in recent years through the development of new techniques (e.g. gravitational lensing) and powerful instruments (e.g. ROSAT, HST). Observations in all wavelengths and the comparison with theory taught us a lot about cluster components, cluster dynamics and the physics in clusters. A particularly interesting aspect has opened up in the last years with the use of clusters as probes for cosmology. The new instruments, e.g. VLT, XMM, CHANDRA and PLANCK, will certainly make cosmology with clusters an even more fascinating field in the future.

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